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APPLICATION OF ARTIFICIAL INTELLIGENCE
TO IMPROVE AIRCRAFT SURVIVABILITY

by

William Leecraft Decker

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Thesis Advisor: Robert E. Ball

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Application of Artificial Intelligence to Improve Aircraft Survivability

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ABSTRACT

The hazards associated with the critical flight phases of civil as well as military flight operations can seriously degrade pilot efficiency, and therefore aircraft survivability, if the number or complexity of tasks that the pilot must manage exceeds his/her capabilities. This thesis explores the feasibility of applying artificial intelligence (AI) research to the construction of a Survivability Manager (SM) knowledge based system (KBS) that will assist the pilot by assuming a portion of the survivability task management load. The application of KBS principles to survivability management is illustrated using the normal and emergency management procedures for a hypothetical engine fuel supply system as a working example. Though the SM is not a reality today, there is considerable research in both AI and survivability enhancement studies to draw upon. It is recommended that a prototype be developed using currently available assets to further investigate the feasibility of the Survivability Manager.

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I. INTRODUCTION

This thesis is concerned with the feasibility of using artificial intelligence to assist the pilot in the management of aircraft survivability design features and equipment. Specifically, the intent is to propose the development of a Survivability Manager, capable of partially or fully autonomous control, for both civil and military aircraft. In order to make the following discussion meaningful, several terms must first be (re)defined.

The aircraft combat survivability discipline has developed a vocabulary based upon a man-made hostile environment. Those familiar with this field will find that several of these terms have been broadened in context here to include their application to civil aircraft. Aircraft combat survivability is defined as "the capability of an aircraft to avoid and/or withstand a man-made hostile environment" [Ref.1: p. 1]. If the term survivability is expanded to include flight safety in general, it could be defined as the capability of an aircraft to avoid and/or withstand a hazardous situation. Similarly, susceptibility is now interpreted as the inability of an aircraft to avoid a hazardous situation, and vulnerability as the inability of an aircraft to withstand a hazardous situation. A hazardous situation is one or more adverse conditions that, by design

or by chance, have the potential to degrade flight performance. Flight performance degradation is measured by the extent to which components, designed to provide that performance, are functionally degraded.

It is recommended that readers who are not familiar with survivability concepts review the glossary provided within this document. Those desiring a more detailed presentation on aircraft combat survivability are referred to Ball [Ref. 1].

II. BACKGROUND : PROBLEM DEFINITION

Since its early development, the aircraft has had to operate under less than ideal circumstances. Even today's super-sophisticated designs are subject to the ravages of defective workmanship, poor maintenance, bad weather, human error, in-flight obstacles, and other aircraft. Military aircraft must withstand man made hazards as well; hazards specifically designed for the destruction of aircraft. There are important distinctions between civil and military hazards, but the pilot's primary responsibility in either case is to ensure that, in spite of any adverse conditions encountered, the flight is safely concluded. This chapter will explore the nature of these hazards, and provide some measure of the trained professional pilot's ability to cope with them.

A. CIVIL AIRCRAFT HAZARDS

The general decline in the number of accidents per flight hour experienced by civil aircraft in the last decade is a direct result of the intensive training and sophisticated equipment currently available to pilots, air traffic controllers, and other support personnel. These impressive statistics notwithstanding, there is always room for improvement. Specifically, the relatively high proportion of

mishaps resulting from human error still gives excellent incentive to take every conceivable effort to reduce them. An analysis of the hazards these aircraft encounter is the first step in any such effort.

1. Mishap Statistics

Each year the National Transportation Safety Board (NTSB) reports statistics concerning aviation related accidents that occur within its jurisdiction. The NTSB defines an accident as an occurence incident to flight in which:

> "as a result of the operation of an aircraft, any person (occupant or nonoccupant) receives fatal or serious injury or any aircraft receives substantial damage." [Ref. 2:p. 80]

The NTSB's latest synopsis covers the period from 1975 through 1984 [Ref. 3]. Although rates (number of accidents per 100,000 flight hours) and even numbers of accidents have generally fallen since 1978, there are still too many. The safest year in recent civil aviation history was 1984, yet there were 173 accidents involving revenue producing flight operations, resulting in 103 fatalities. Revenue producing operations include airlines, commuters, and on-demand air taxis. The statistics also reveal 2999 general aviation accidents in 1984, with 998 fatalities. General aviation operations refer to private, non-revenue producing, flying. The number and rate for this category are much higher, due, among other factors, to the enormous number of general

aviation aircraft. Unofficially, 1985 has already surpassed these figures, and is recognized as one of the worst years in recent civil aviation history [Ref. 4:p. 1].

2. Accident Causes/Factors

In an effort to identify trends and significant problem areas, the NTSB reports all probable cause(s), as well as any related factors, for each accident. Factors are those elements of an accident that further explain or supplement the probable cause(s). These cause/factor elements may be grouped into three general categories:

1) Environmental extreme.
2) Material failure.
3) Human error.

Environmental extremes include micro-bursts, wind shear, turbulence, low visibility, hail, birds, and wet runways. Cyclic fatigue, brittle fracture, electrical malfunction, and fluid seal rupture are all examples of material failures. Human errors are procedural and judgemental errors on the part of the designer, manufacturer, pilot, air traffic controller, weather briefer, maintenance and service personnel, and any others directly or indirectly responsible for flight safety. Of all the causes/factors listed, pilot error is cited most often.

3. Critical Flight Phases

In reviewing accident statistics, it soon becomes apparent that there are operational flight phases which are more hazard intensive than others.

According to the NTSB [Ref. 2], the five general flight phases are:

1) Static - aircraft immobile on deck, engines idle or secured.
2) Taxi - to takeoff or from landing.
3) Takeoff - run, abort, initial climbout.
4) In Flight - climb to cruise, normal cruise, descent.
5) Landing - approach, touchdown, roll out, missed approach.

For the 1976-1981 period the NTSB reported that U. S. air carriers sustained 58% of their accidents while in the takeoff or landing phases.

4. <u>Hazards of Success</u>

The capabilities, availability, and popularity that the aircraft has gained in the past eighty years has made it indispensable to modern civilization. It is ironic that this success has, in a sense, increased the opportunity for mishap. Aircraft have become bigger, faster, and more numerous, and each of these advantages has a corresponding disadvantage.

a. Aircaft Size

The first commercial flight service was in 1919, between London and Paris. The aircraft carried a maximum of four passengers. Today, 'jumbo jets' carry up to five hundred passengers from New York to Tokyo, nonstop. These behemoths weigh over 400 tons and span almost 200 feet, wing tip to wing tip. That is too many people with too much inertia to expect favorable results in a mishap.

b. Flight Speed

History's first fatal accident in a powered aircraft occurred in 1908. Lieutenant Thomas Selfridge was killed as a result of a biplane crash, of which he was the passenger. The pilot was Orville Wright. The top speed of the craft was almost 45 miles per hour, apparently fast enough to kill.

Today, supersonic transport (SST) air carriers cross the Atlantic at Mach two plus. More commonly, large subsonic transports cruise at about Mach point eight, which is roughly one thousand feet per second. The obvious hazard of an irresistible force meeting an immovable object is compounded by 1) the limited reaction time available to prevent it and 2) the possibility that the pilot is not even aware of the hazard.

c. Traffic Density

The number of IFR flights handled by the Federal Aviation Administration (FAA) Air Route Traffic Control Centers (ARTCC) has increased from 20.6 million in 1969 to 31.6 million in 1984. The FAA forecasts the number to rise to 45.3 million in 1996 [Ref. 5:p. 1]. The total number of aircraft actually in the air is even greater, due to the VFR traffic that is not handled by the ARTCC. In 1984, the FAA recorded 42.9 million IFR flight hours, which reduces to an average of 4,897 IFR aircraft within U.S. airspace at all times. This means that the airways are getting more crowded,

en route delays will become more frequent and last longer, and the opportunities for collision will rise accordingly.

B. MILITARY AIRCRAFT HAZARDS

A major portion of military flight operations occurs in non-combat conditions, even in time of war. The previous discussion concerning civil aircraft hazards applies equally to military aircraft in these conditions. While in combat, the military pilot must also cope with a determined enemy effort to shoot him down. In this condition, the hazards can be of either external or internal origin. The external hazards are provided by the enemy air defense system, and the internal hazards are associated with task overload.

1. Sophistication of Air Defense Systems

The proliferation of air defense systems which have been developed to counter the threat of aggressor aircraft is an acknowledgement of the potential destructive power of these aircraft. With each gain in air power sophistication, there has been an effective countermeasure developed to neutralize it. Today, there are radar directed, high kinetic energy guns; long range guided surface-to-air and air-to-air missiles; and state-of-the-art high performance fighter interceptors, capable of engaging multiple targets simultaneously. Still under development are directed energy weapons, using high power lasers and particle beams. The list is endless, and the combat pilot must have the means to

cope with these threats if he is expected to perform effectively and repeatedly.

2. Sophistication of Aircraft

Advances in technology, particularly in the last twenty-five years, have nurtured the development of aircraft capable of extremely complex operations under extraordinary environmental conditions at incredibly high speeds. This sophistication has brought two disturbing consequences. The first is the concurrent improvements in air defense system technology, discussed above. The second is the increasing probability that the pilot will encounter task overloading during critical flight phases, resulting in a fatal procedural oversight. The number of cockpit controls and displays has increased exponentially since the 1920s. The result is a 'data rich, information poor' pilot, who must make timely, effective use of it. The pilot must be constantly cognizant of the aircraft health status, stores inventory, navigational position, and tactical situation, while simultaneously flying the aircraft, obtaining a fire control solution, selecting munitions, employing air defense countermeasures, evaluating component failure consequences, and updating response priorities. Although some of these tasks are currently being automated to some degree, the potential for pilot overload during critical mission phases is still very significant.

C. HUMAN PERFORMANCE

Given the hazards outlined above, the capability for rapid, effective action to prevent or minimize critical component loss due to failure or damage must be enhanced correspondingly. Trained professional pilot capabilities notwithstanding, there is a limit to the number and complexity of operations that a person can perform in a given amount of time. Pilot functional overload is reached when:

(1) Response time exceeds safe reaction time or;
(2) Reaction complexity exceeds response capabilities.

Human capabilities and limitations have been characterized by the Air Force Studies Board. Humans, as a system component, can perform numerous mission and flight essential functions which are not otherwise possible. They have well developed perceptual abilities, including visual and aural discrimination, pattern recognition, and speech comprehension. They are capable of flexible control, in that they can readily invent new procedures and adapt old ones to new circumstances. An unavoidable partner to this flexibility is a requirement for motivation. Humans perform best in active, mentally stimulating conditions, thus making them poor at repetitive tasking and watch-keeping. [Ref. 6:p 34]

The human brain possesses limited information processing capabilities. The speed at which data can be absorbed, processed, and responded to is finite, and can not be

appreciably increased. In addition, the human brain is basically a serial processor, able to perform multiple tasking only by rapidly switching through each one. [Ref. 6:p 35]

The errors associated with human information processing include precision, capture, and sequential errors. Precision errors are characterized by the incorrect identification of a state among many similar but distinct states. Capture errors occur when an incorrect, but familiar procedure is executed in place of the correct, less familiar one. Sequential errors refer to the improper order of step execution for a given procedure. The number and severity of the errors go up as the tasking increases. [Ref. 6:p 36]

III. OBJECTIVE : AUTOMATE AIRCRAFT SURVIVABILITY MANAGEMENT

Given the capabilities and limitations of human performance, there are three options available to enhance pilot effectiveness during critical (high workload) flight phases:

(1) Improve pilot selection and training.
(2) Increase the crew size.
(3) Build 'intelligent' cockpits.

Option one would not be cost effective, because the calibre of today's trained professional pilot is probably near the peak of human capability. The cockpit workload is simply threatening to exceed this capability. Option two has historically provided a workload reduction by delegation, but there are several disadvantages associated with the additional personnel. For example, it has been estimated that each additional 150-pound person in the cockpit requires approximately 10,000 pounds of additional support equipment [Ref. 6:p. 36]. It may be of greater importance to note that, ironically, the additional personnel does not always provide better performance. Complacency can compromise safety in a multi-piloted aircraft, when division of task load is not clearly defined. Recent design philosophy has shifted to one man operable cockpits, in part, for these reasons. Examples include the F-16, F/A-18, F-20, LHX, ATA,

ATF, and CASP. Even so, the Navy is now studying a proposal by McDonnell Aircraft Company for the development of a two seat operational version of the F/A-18 [Ref. 7]. The justification given implies that the additional crewman provides capabilities not otherwise possible with the automation technology that is curently available. Regardless of the number of seats, this conventional technology provides the pilot (and crew) with execution aids that, as opposed to autonomous employment aids, may not adequately reduce pilot tasking in critical flight phases. Building 'intelligent' cockpits, as option three suggests, could theoretically provide this needed reduction. There are numerous facets of the cockpit environment that could benefit from this 'built in' intelligence, but this thesis is concerned with survivability. Therefore, consider the incorporation of a system specifically designed to actively assist the pilot in maximizing the aircraft's survivability; a Survivability Manager.

A. THE SURVIVABILITY MANAGER

Whether civilian or military, the pilot is charged with three major responsibilities. In descending order of importance, they are:

(1) Safety of personnel.
(2) Effective employment of the aircraft.
(3) Mission objectives.

Any attempt to improve pilot performance must be measured against his/her success in meeting these goals. The most important measure of this success is survivability. With the advent of cockpit automation, pilot performance (and therefore survivability) has increased significantly. A logical next step is to automate the management of survivability features and equipment; that is, give the aircraft a Survivability Manager designed to actively prevent or minimize any flight performance degradation that might result from a hazardous situation.

The extensive use of microprocessor technology in modern aircraft design has provided subsystem status and control as a base on which to build. For example, most automated systems have built-in-test capabilities that self diagnose functional health. These data bases could be drawn upon by the Survivability Manager to monitor aircraft health and performance potential. Since many of these same subsystems are also computer operated, they may, in theory, be managed by a computer possessing 'quasi-human' intelligence. Suppose, for example, that a component failure is detected. The Survivability Manager would selectivly reconfigure the remaining operational subsystems to functionally replace the failed component. The pilot has historically performed the reconfiguration, but a computer with a modest inference capability could also do it.

B. AUTOMATION GUIDELINES

In selecting the functions to be automated, careful consideration must be given to the amount of interaction desired between the pilot and the Survivability Manager. A strict division of functional responsibilities is not necessarily desirable. The degree of automation must be carefully considered for each potential application. According to Air Force studies [Ref. 6:p. 39], the degree of automation employed should reflect the need to:

(1) Reduce excessive workload.
(2) Reduce errors.
(3) Improve performance.
(4) Add new capabilities.

Computers will never be truly intelligent, like people. The subtle nuances and intuitive creativity of the human mind are beyond the physics of semiconductors. It is therefore difficult to conceive that pilots could be automated out of a job (the limited utility of remotely piloted vehicles (RPV) notwithstanding). However, there are many tasks that computers can perform as well as or better than people. They can complement pilot abilities by performing routine tasking or watch-keeping. In addition, they can supplement or extend pilot abilities. A case in point is the fly-by-wire flight control system for the DARPA X-29 forward swept wing aircraft. The dynamic instability of the aircraft is such that, without computer control, it would be ripped apart in a

fraction of a second. The pilot simply can not react quickly enough or precisely enough to directly control the aircraft.

C. LIMITATIONS TO CURRENT AUTOMATION METHODS

Conventional programming logics rely on exhaustive search and numeric methods to solve problems. These algorithms are incredibly fast at exceedingly tedious mathematical calculations, making them effective tools for automation of routine or well defined tasks. They do not lend themselves well to rational processes, where non-numeric facts and constraints must be considered. The conventional language program (such as FORTRAN) possesses a rigid response framework, from which it will analyze data and formulate results. To require such a program to select an optimal solution based on non-numeric considerations would invariably invite disaster. What is required is a pseudo-intelligent program, one that can reason in a quasi-human fashion; hence the term,"Artificial Intelligence".

IV. APPROACH : ENHANCE SURVIVABILITY WITH ARTIFICIAL INTELLIGENCE

Artificial Intelligence (AI) can be loosely defined as the condition wherein machines think, or at least seem to think, like people. Specific research in this relatively new field of study includes natural language, vision, symbolics, robotics, and expert systems. Expert systems, also referred to as knowledge based systems (KBS), are the AI studies to be addressed here. These systems use sophisticated problem solving techniques and vast stores of knowledge to solve problems that conventional programming methods can not.

A. THE KNOWLEDGE BASED SYSTEM

In order to build knowledge based systems, the software engineer must first be aware of the techniques that the human mind uses, consciously or not, to attack difficult problems, and the reasoning strategies used to guide the search for solution(s). According to Lenat [Ref. 8:p. 204], humans solve problems by applying their understanding of the regularities of the solution space to constrain the search. The techniques used to apply this understanding include:

1) Formal reasoning: use formal logic methods such as resolution or structural induction.

2) Heuristic reasoning: use statistical probability methods and if-then rules of thumb.

3) Focus: be oriented toward specific goals.

4) Divide and conquer: break up a complex problem into smaller, simpler problems.

5) Parallelism: work on several searches simultaneously.

6) Representation: attack the problem from several different perspectives.

7) Analogy: recognize the similarities of a new problem to an old one.

8) Synergism: use a multitude of simple relationships to solve a complex problem.

9) Serendipity: gather data and look for patterns.

It is essential to incorporate these techniques in the construction of the expert system if it is to succeed at performing intelligently, but it is not sufficient. There must also be a reasoning strategy that guides the employment of these techniques. The two most common reasoning strategies are forward inferencing and backward inferencing. In forward inferencing the attempt is made to reason forward from the facts to a solution. In backward inferencing the system will assume a solution and try to find supporting evidence from the facts.

Assuming that the KBS is constructed to employ the requisite reasoning techniques and strategies, it must also have access to an enormous amount of basic knowledge. This knowledge base must be comprehensive and unpolluted in order to prevent deductive errors. Deductive errors include errors of omission (a known fact that is not provided), and errors

of commission (information input that is inaccurate). Moreover, there is a fundamental limitation to which any logical reasoning process is subject: insufficient data. In other words, if "THIS follows from THAT" can be validated, then the system will answer YES. But if "THIS does not follow from THAT", given an incomplete knowledge base, the system may not be able to answer NO. In order to obtain a KBS relatively free of deductive errors, the process of acquiring the knowledge from domain experts must be meticulous and exhaustive. Current techniques for knowledge acquisition are slow and painful, and if AI is to become truly practical, a more automatic means must be devised.

When the rational thought processes are clearly understood, the software engineer can then begin to construct the knowledge based system (Figure 1). Fundamentally, this consists of a knowledge base and an inference engine [Ref. 9:pp. 22-23]. The knowledge base is the store of facts and rules, provided by the domain expert, which pertain to the subject of interest. The inference engine performs the actual reasoning process using a combination of the reasoning tools and strategies described above.

The inference engine is essentially a program that is capable to processing symbols that represent objects. In

```
      Assertions                          Question
          |                                  |
          V                                  V
   [Knowledge Base]----------->[Inference Engine]
                                             |
                                             V
                                        Answer(s)
```

Figure 1. Knowledge Based System

contrast to conventional computer applications, where symbols represent numbers and mathematical operations, the KBS symbol can represent a person, process, concept, or class of objects. The knowledge can be represented in several different formats, with each format used for the knowledge it represents best [Ref. 10:p. 32]:

(1) Production rules; situation-action or premise-conclusion rules in which the first part (antecedent) represents some pattern, and the second part (consequent) represents a conclusion to be drawn when the data matches the pattern. They are useful in representing procedural knowledge.

(2) Semantic networks; taxonomic scheme wherein objects are nodes and relationships are links between nodes. They are useful in representing object interrelationships.

(3) Frames; format in which objects are represented by certain standard properties and by relationships with other objects. They are useful in representing large amounts of knowledge about object properties and relations.

(4) First order logic; formal method of representing logical propositions and relationships between propositions. Useful in representing knowledge in explicit terms.

Ideally, the knowledge would be encoded within the knowledge base in the format that provides for the most efficient utilization for the current problem.

B. A SIMPLE KBS ILLUSTRATION

A practical example will now be presented to illustrate the applicability of the KBS to aircraft survivability. The application to be considered incorporates both susceptibility reduction and vulnerability reduction logics for a simplified twin-engine aircraft fuel supply system. This fuel supply system consists of identical port and starboard subsystems which feed the port and starboard engines, respectively. The primary components of each subsystem include a feed tank, a transfer tank, and an external tank. The susceptibility reduction logics seek to avoid fuel starvation, through proper management of the available fuel supply. The vulnerability reduction logics seek to minimize the loss of usable fuel due to component failures. The domain knowledge, which is encoded into the knowledge base, will be partially represented by a set of production rules, which would be provided by the domain expert (in this case the fuel system engineer). In this example, the rules may be divided into two groups; declarative rules and procedural rules. When the declarative rule antecedent conditions are satisfied, the SM

adds the consequent to the knowledge base as an assertion. When the prcedural rule antecedent conditions are satisfied, the SM performs, or advises the pilot to perform, some action(s). In addition to the production rules, the knowledge base also contains facts that represent status of the fuel supply system's critical components. These component status facts are continuously updated by reports from appropriate sensors.

In a situation where probabilities must be considered, each declarative rule antecedent condition would be 'tagged' with its derived probability. The probability of the consequent would then be computed using Bayes' law or some other formal procedure of probability theory. For this example, all probabilities will be assumed to be 100 percent. In the following list of rules, the local variable 'X' stands for either starboard or port, and is necessarily consistent only within a given rule. The local variable 'Y' always stands for the opposite to the value of local variable 'X'. This effectively cuts the number of required rules in half, with a corresponding savings in required memory. A (D) is used to identify a declarative rule, and a (P) identifies a procedural rule.

RULES:

(1) IF FUEL FLOW PRESSURE TO ENGINE X IS HIGH, THEN ENGINE X WILL HAVE SUFFICIENT FUEL TO MEET ENGINE X DEMANDS. (D)

(2) IF (FUEL FLOW PRESSURE TO ENGINE X IS LOW) AND (THROTTLE X IS CHANGED ABRUPTLY), THEN ENGINE X WILL CEASE TO FUNCTION. (D)

(3) IF FUEL FLOW PRESSURE TO ENGINE X IS ZERO, THEN ENGINE X WILL CEASE TO FUNCTION. (D)

(4) IF (FUEL IS AVAILABLE TO ENGINE X BOOST PUMP) AND (ENGINE X BOOST PUMP FUNCTIONS), THEN FUEL FLOW PRESSURE TO ENGINE X IS HIGH. (D)

(5) IF (FUEL IS AVAILABLE TO ENGINE X BOOST PUMP) AND (ENGINE X BOOST PUMP FAILS FREE), THEN FUEL FLOW PRESSURE TO ENGINE X IS LOW. (D)

(6) IF (FUEL IS NOT AVAILABLE TO ENGINE X BOOST PUMP) OR (ENGINE X BOOST PUMP FAILS FROZEN), THEN FUEL FLOW PRESSURE TO ENGINE X IS ZERO. (D)

(7) IF (FUEL IS AVAILABLE TO FIREWALL SHUTOFF VALVE X) AND (FIREWALL SHUTOFF VALVE X IS OPEN), THEN FUEL IS AVAILABLE TO ENGINE X BOOST PUMP. (D)

(8) IF (FUEL IS NOT AVAILABLE TO FIREWALL SHUTOFF VALVE X) OR (FIREWALL SHUTOFF VALVE X IS CLOSED), THEN FUEL IS NOT AVAILABLE TO ENGINE X BOOST PUMP. (D)

(9) IF (ENGINE X BOOST PUMP FAILS FROZEN) OR (FEED TANK X EJECTOR PUMP IS CLOGGED) OR (ENGINE X FUEL DEMAND IS ZERO), THEN CLOSE FIREWALL SHUTOFF VALVE X. (P)

(10) IF (FEED TANK X QTY IS NOT ZERO) AND (FEED TANK X EJECTOR PUMP IS CLEAR), THEN FUEL IS AVAILABLE TO FIREWALL SHUTOFF VALVE X. (D)

(11) IF (FEED TANK X QTY IS ZERO) OR (FEED TANK X EJECTOR PUMP IS CLOGGED), THEN FUEL IS NOT AVAILABLE TO FIREWALL SHUTOFF VALVE X. (D)

(12) IF (FEED TANK X FUEL QTY IS LESS THAN MINIMUM) AND (FIREWALL SHUTOFF VALVE X IS OPEN), THEN (OPEN FEED TANK INTERCONNECT VALVE) AND (FLY WINGS LEVEL). (P)

(13) IF (FEED TANK X QTY IS FULL) AND (FUEL CAN NOT BE TRANSFERRED FROM EXTERNAL TANK X OR TRANSFER TANK X TO FEED TANK X), THEN CLOSE THE FEED TANK INTERCONNECT VALVE. (P)

(14) IF (TRANSFER TANK X EJECTOR PUMP FUNCTIONS) AND (TRANSFER TANK X QTY IS NOT ZERO), THEN FUEL IS TRANSFERRED FROM TRANSFER TANK X TO FEED TANK X. (D)

(15) IF (FEED TANK X IS FULL) AND (FUEL IS TRANSFERRED FROM EXTERNAL TANK X OR TRANSFER TANK X OR FEED TANK Y TO FEED TANK X), THEN EXCESS FUEL IS VENTED TO TRANSFER TANK X. (D)

(16) IF (TRANSFER TANK X QTY IS ZERO) OR ((EJECTOR PUMP FAILS) AND (TRANSFER TANK X CHECK VALVES FAIL CLOSED)), THEN FUEL CAN NOT BE TRANSFERRED FROM TRANSFER TANK X TO FEED TANK X. (D)

(17) IF (EXTERNAL TANK X QTY IS NOT ZERO) AND (THE EXTERNAL TANK PRESSURIZATION VALVE IS OPEN), THEN FUEL IS TRANSFERRED FROM EXTERNAL TANK X TO FEED TANK X. (D)

(18) IF (EXTERNAL TANK X QTY IS ZERO) OR (THE EXTERNAL TANK PRESSURIZATION VALVE FAILS CLOSED), THEN FUEL CAN NOT BE TRANSFERRED FROM EXTERNAL TANK X TO FEED TANK X. (D)

(19) IF EXTERNAL TANK X QTY IS GREATER THAN ZERO AND LESS THAN TRANSFER TANK X (CAPACITY MINUS QTY), THEN OPEN EXTERNAL TANK PRESSURIZATION VALVE. (P)

(20) IF (EXTERNAL TANK X QTY PLUS EXTERNAL TANK Y QTY IS ZERO) AND (THE EXTERNAL TANK PRESSURIZATION VALVE IS OPEN), THEN CLOSE THE EXTERNAL TANK PRESSURIZATION VALVE. (P)

(21) IF (FEED TANK INTERCONNECT VALVE IS OPEN) AND (WING X IS LOWER THAN WING Y), THEN FUEL IS TRANSFERRED FROM FEED TANK Y TO FEED TANK X. (D)

(22) IF (FEED TANK INTERCONNECT VALVE IS CLOSED) OR (FEED TANK Y QTY IS ZERO) OR (WING Y IS LOWER THAN WING X) OR (FEED TANK X AND TRANSFER TANK X QTY IS FULL), THEN FUEL CAN NOT BE TRANSFERRED FROM FEED TANK Y TO FEED TANK X. (D)

(23) IF FUEL TANK X INTEGRITY IS SEALED, THEN FUEL TANK X WILL HOLD UP TO FUEL TANK X CAPACITY UNTIL SUCH FUEL IS TRANSFERRED OUT OF FUEL TANK X. (D)

(24) IF (EXTERNAL TANK X IS RUPTURED) AND (EXTERNAL TANK X QTY IS NOT ZERO), THEN OPEN THE EXTERNAL TANK PRESSURIZATION VALVE. (P)

(25) IF (TRANSFER TANK X IS RUPTURED) AND (FUEL CAN BE TRANSFERRED FROM EXTERNAL TANK X OR TRANSFER TANK X TO FEED TANK X), THEN (OPEN THE FEED TANK INTERCONNECT VALVE) AND (FLY WING Y DOWN). (P)

FACTS:

(1) RH EXTERNAL TANK QTY IS (ZERO/PARTIAL/FULL).

(2) LH EXTERNAL TANK QTY IS (ZERO/PARTIAL/FULL).

(3) RH TRANSFER TANK QTY IS (ZERO/PARTIAL/FULL).

(4) LH TRANSFER TANK QTY IS (ZERO/PARTIAL/FULL).

(5) RH FEED TANK QTY IS (ZERO/MIN/PARTIAL/FULL).

(6) LH FEED TANK QTY IS (ZERO/MIN/PARTIAL/FULL).

(7) RH EXT TANK INTEGRITY IS (SEALED/RUPTURED).

(8) LH EXT TANK INTEGRITY IS (SEALED/RUPTURED).

(9) RH TRANS TANK INTEGRITY IS (SEALED/RUPTURED).

(10) LH TRANS TANK INTEGRITY IS (SEALED/RUPTURED).

(11) RH FEED TANK INTEGRITY IS (SEALED/RUPTURED).

(12) LH FEED TANK INTEGRITY IS (SEALED/RUPTURED).

(13) RH ENGINE BOOST PUMP IS (FROZEN/FREE/FUNCTIONAL).

(14) LH ENGINE BOOST PUMP IS (FROZEN/FREE/FUNCTIONAL).

(15) RH FEED TANK EJECTOR PUMP IS (CLOGGED/CLEAR).

(16) LH FEED TANK EJECTOR PUMP IS (CLOGGED/CLEAR).

(17) RH TRANSFER TANK EJECTOR PUMP IS (CLOGGED/CLEAR).

(18) LH TRANSFER TANK EJECTOR PUMP IS (CLOGGED/CLEAR).

(19) FEED TANK INTERCONNECT IS (CLOSED/OPEN).

(20) RH FIREWALL SHUTOFF VALVE IS (CLOSED/OPEN).

(21) LH FIREWALL SHUTOFF VALVE IS (CLOSED/OPEN).

(22) EXTERNAL TANK PRESSURIZATION VALVE IS

(CLOSED/OPEN).

(23) RH WING IS (HIGHER/LOWER) THAN LH WING.

Consider the knowledge base above. The SM's function, with regard to the fuel supply system, is to ensure that fuel is available to meet engine demands as long as possible. This maintained availability is the desired goal state toward which the SM must constantly strive. It is therefore logical to use a backward inferencing strategy to achieve this goal state. As an initial state, suppose all components are functioning correctly (as would normally be the case), and that all six fuel tanks are full of fuel. The SM will be monitoring both port and starboard fuel supply subsystems simultaneously. If the fuel supply to the starboard engine is of current interest, then 'X' corresponds to starboard, and 'Y' corresponds to port. Starting with the consequent of Rule 1 (i.e. ENGINE X WILL HAVE SUFFICIENT FUEL TO MEET ENGINE X DEMANDS) as the hypothetical result, the inference engine attempts to satisfy the conditions of the antecedent (i.e. FUEL FLOW PRESSURE TO ENGINE X IS HIGH). It searches the knowledge base for a sequence of actions, combined with current facts, that will culminate in the maintenance of these conditions.

Although the fuel flow pressure is in fact already high in the initial state, it is not guarenteed to stay high. Therefore, the SM continuously cycles through the knowledge

base, searching for a sequence of actions to take that will ensure that the fuel flow pressure remains high for as long as possible. In this way, the SM finds that the consequent of Rule 4 satisfies the antecedent of Rule 1; that Fact 13 (functional boost pump) and the consequent of Rule 7 combine to satisfy the antecedent of Rule 4; that Fact 20 (open firewall shutoff valve) and the consequent of Rule 9 combine to satisfy the antecedent of Rule 7; and finally, that Fact 5 (full feed tank) and Fact 20 (clear ejector pump) combine to satisfy the antecedent of Rule 9. Thus the, initial state conditions (facts) are sufficient to achieve the goal state conditions (hypothesis), as long as the initial conditions due not change. However, conditions must change; fuel must flow.

As the feed tank fuel is transferred to the engine, the transfer tank automatically replenishes the feed tank, via the transfer tank ejector pump and check valves (Rule 14). This transfer rate is greater than any engine demand rate possible, and the excess is vented back into the transfer tank (Rule 15). All of this happens without SM intervention. The SM will intervene only when procedural rules are fired (i.e. the antecedent is satisfied).

When the quantity of fuel in the transfer tank plus the quantity of fuel in the external tank is less than the fuel capacity of the transfer tank, the antecedent of Rule 19 is satisfied and the SM directs that the external tank

pressurization valve be open. If completed, this action is reflected by a change in Fact 22 (pressurization valve open) which, along with Fact 1 (external tank full), satisfies Rule 17. Rule 17 then 'asserts' that fuel is transferred from the external tank to the feed tank. Finally, by Rule 15, the transfer tank is replenished until, by Rule 20, the external tank pressurization valve is closed.

Now, suppose that the starboard transfer tank begins to lose fuel and that the appropriate sensor reports this failure. Ideally, the sensor would report the failure cause, mode, and degree. In this example, the mode is reported to be a loss of usable fuel, the cause might be projectile penetration, and the degree might be a gallon per minute. Although the cause and degree of the fuel loss may not be easily assessed, knowledge of the failure mode supplies sufficient data for the SM to attempt to minimize the degradation of fuel system performance. Rule 25 is fired by the reported failure, causing the SM to direct the opening of the feed tank interconnect valve and the lowering of the left wing. These actions update Fact 19 (interconnect open) and Fact 23 (left wing down), which allows fuel to be transferred to the port fuel tanks. This action conserves fuel that would otherwise be lost via the leaking tank. When the starboard feed tank quantity drops below a predefined minimum, Rule 12 is fired, which allows the port feed tank to refill the starboard feed tank. When the starboard feed tank

is again filled, Rule 13 is fired, which prevents fuel from being vented back into the ruptured tank. The SM will then cycle between Rule 12 and Rule 13 until a new fact fires some other rule(s) into action.

This example has been oversimplified in the interest of brevity and clarity. Obviously, there are other effects to consider, such as fire hazards or significant structural damage, associated with the damage/failure processes that led to the loss of integrity of the starboard fuel transfer tank. In addition, the remedial actions taken must be weighed against possible adverse affects on the performance of other systems. In this case, the flight control system may not be able to trim out the lateral weight imbalance resulting from the fuel redistribution from the starboard wing to the port wing. It is assumed that the knowledge base would be comprehensive enough to enable the SM to foresee and resolve such conflicts, within the paramount constraint to sustain controlled flight as long as possible.

V. AI APPLICATIONS TO AIRCRAFT SURVIVABILITY

Aircraft combat survivability enhancement studies emphasize the needs of the military aircraft in combat conditions. Specifically, they seek to prevent enemy air defenses from engaging friendly aircraft (susceptibility reduction) and/or limit the damaging effects of such engagements (vulnerabilty reduction). However, these studies are not exclusively applicable to military aircraft in combat conditions. For example, the development of collision avoidance equipment for civil aircraft is also an application of susceptibility reduction principles. Similarly, vulnerability reduction studies are relevant to all aircraft, in that they are concerned with component failures which may or may not be the result of damage that is intentionally inflicted. Whether the aircraft is civil or military, artificial intelligence will have widespread application assisting the pilot in managing the systems involved. With a Survivability Manager on board, the pilot will be free to concentrate on flight safety and mission objectives.

A. SUSCEPTIBILITY REDUCTION

1. Military Aircraft

There are six general concepts which can be employed to reduce the susceptibility of military aircraft to combat

damage: threat warning, noise jammers and deceivers, signature reduction, expendables, threat suppression, and tactics [Ref. 1:pp. 198-221]. All of them can be enhanced to some degree by AI management.

a. Threat Warning

Any on board equipment that senses and analyzes enemy electromagnetic emissions must make this data useful to the pilot. Simply inundating him/her with nonprioritized and possibly extraneous data may well serve to lessen his/her effectiveness, rather than increase it. He/she is primarily concerned with the enemy's tracking, illuminating, and guidance emitters, and he/she must react to these emitters in the order of descending response urgency. AI is capable of servicing these requirements. In addition, the emitter classification and status determination can clearly benefit from AI's ability to draw logical inferences from bodies of evidence of various levels of abstraction inherently containing some degree of uncertainty.

b. Noise Jammers and Deceivers

Timely and effective employment of these electromagnetic countermeasures devices is dependent on careful consideration of the dynamic tactical environment in which the aircraft is operating. Obviously, this is an area where the pilot could use an 'assistant' to suggest or actively control such employments. The Survivability Manager

could provide this assistance, given that it has access to a knowledge base describing the tactical environment.

c. Signature Reduction

The aircraft signature includes radar cross section, infrared radiation, visible and acoustic emissions, and electromagnetic emissions from active sensors and communications equipment. The state of current technology could provide the pilot, and so the SM, with signature reduction features that give some control over the magnitude of these detectable emissions. For example, an electromagnetic (EM) emitter master disable switch could be provided, to effect total EM silence instantly on demand. The optimum utilization of these features can be suggested, or autonomously effected, by a properly programmed SM.

d. Expendables

Arguments identical with item (b).

e. Threat Suppression

This refers to actively neutralizing the threat through weapons employment. Although AI would undoubtedly find application with offensive tactical weapons employment, it is an entire study in itself, and will not be pursued here.

f. Tactics

Tactics refer to the way in which the aircraft is employed in combat. An example of a tactic used to reduce aircraft susceptibility is to fly an aircraft profile that

will minimize the exposure time to the threat. The SM could suggest defensive tactics if, as assumed in item (b), it has access to knowledge bases concerned with the mission requirements and the tactical environment.

g. Integrated Features

The greatest potential will be achieved with a Survivability Manager designed to use an integrated systems approach. For example the data from threat warning devices could be analyzed to allow maximum effectiveness in the various countermeasures employments. In addition, the information could be presented so as to suggest defensive maneuvers (tactics) that would give the threat emitters the widest possible berth.

2. Civil Aviation Aircraft

Most of the susceptibility reduction techniques apply only in man-made hostile environments. Threat warning stands out as the notable exception when the term 'threat' includes those which are non-military. Within this definition, threats include environmental extremes, material failures, and human errors.

a. Environmental Extreme

Currently, most of the information that is provided to the pilot concerning environmental extremes comes, if at all, from sources outside of the aircraft. These sources include preflight weather briefs, in flight updates from Flight Service Stations, and Pilot Reports.

Weather radars are the only widely available on board device capable of warning of weather hazards, and they are limited to the detection of thunderstorms and heavy precipitation. The development of aircraft wind shear detection systems will provide a real time alert for wind shear hazards, allowing the pilot to better prepare for their effects. The sensor data could also be fed to the SM, which could then suggest (if not execute, in time critical situations) steps to avoid or withstand the threat. Like the pilot, the SM will be most effective when the aircraft sensors can provide a nearly complete picture of the external environment.

b. Material Failure

Component material failures generally can not be accurately predicted in flight. Either they are long term phenomena, monitored by sophisticated ground maintenance equipment and replaced well before failure occurs, or they fail too rapidly to allow any pilot warning. However, there are situations where appropriate action can be taken in flight to avoid specific component failures. For example, strain gages might be placed at strategic stress points in the wing structure. The data from these sensors could be compared with known structural strength limits to conitnuously update the 'g' load limits. In the event of unavoidable overstress conditions or structural damage, the pilot would have a means to asses the new 'g' load that may be safely applied to the aircaft. This principle of health

awareness can be applied throughout the aircraft, giving the SM the means to monitor the material strenth of major load bearing components and to take steps to prevent them from failing.

c. Human Error

The threat of human error is probably the hardest to detect, due to the complex and unpredictable nature of the human mind. Nevertheless, many errors can be detected in the period after commission and prior to any irreversible consequences. Since pilot error is the most often cited cause/factor in accident investigation reports, it may be inferred that the complacent and/or inexperienced pilot is currently the most serious threat to aviation safety. Though no amount of assistance can replace good judgment or professional airmanship, a timely caution might have saved many competent pilots from their one fatal mistake. An SM programmed to monitor normal and emergency procedures, with status sensor relays from the controls involved, could warn against, if not actively prevent, such procedural blunders. This is a logical sophistication of the warning, caution, and advisory lights, which are designed as procedural decision aids for the pilot.

B. VULNERABILITY REDUCTION

Vulnerability reduction features attempt to minimize the degradation of aircraft performance as the result of combat

damage. There are six general concepts used in the design of these features [Ref. 1:pp. 269-306]:

(1) Component redundancy (with separation).
(2) Component location.
(3) Component shielding.
(4) Component elimination.
(5) Passive damage suppression.
(6) Active damage suppression.

Although designed specifically for the reduction of vulnerable area presented to a combat damage mechanism, these concepts may be applied to aircraft vulnerability reduction for threats in general. Most of the vulnerability reduction techniques are hardware design options, and do not lend themselves to direct pilot (or SM) control. The exceptions are active damage suppression and component redundancy, seperately or in combination.

Active damage suppression features reduce vulnerability by containing or minimizing the terminal effects of a damage mechanism to a critical component, contingent upon detection of those terminal effects by an appropriate sensor. For example, the penetration (the terminal effect) of an engine lube oil sump (the critical component) by a blast generated fragment (the damage mechanism) will lead to the eventual seizure of the engine. The engine oil pressure guage indicates the resulting loss in oil pressure, allowing the pilot to preemptively secure the engine. Although the engine is functionally lost in either case, the difference in pilot action could make the difference in surviving the loss.

Component redundancy is achieved when the flight essential function (eg. lift, thrust, or control) that a component is designed to provide is preserved, even after the functional loss of that component. Ideally there will be several alternative components, or groups of components, which are capable of performing the same essential function. This critical component redundancy may be physical or functional, partial or total, concurrent or contingent. If it is contingent, there must be some controlling mechanism that will sense the failure and subsequently activate the redundancy. In its simplest form, the redundancy activation mechanism can be reflexive, as in the deployment of a ram air turbine when total loss of electrical power is sensed by a solenoid. This technique is of limited application where the complexity and degree of degradation require careful consideration in the context of the current operational environment. For example, consider a Navy tactical aircraft making a field recovery. Failure of the landing gear breaking system during the landing roll may dictate either a long field arrestment or a go-around to a short field arrestment. Automatically lowering the arresting hook upon break failure is not an appropriate remedy, and could in fact lead to disasterous consequences. In such cases, a more sophisticated mechanism is required to activate the redundancy. This sophistication can be provided by either the pilot or the Survivability Manager.

The principles of component redundancy and active damage suppression can be applied together to synergistically improve aircraft survivability. For example, a redundant control rod that is jammed (the terminal effect), as a result of blast-generated fragment impact (the damage mechanism), could be disengaged from the control linkage by means of an override switch (the active damage suppression feature). Once the jammed component is correctly identified by the appropriate sensor, the pilot or the SM could disengage the jammed rod (active damage suppression) and engage the remaining functional rod (component redundancy).

The most productive method for determining the functional redundancies available for a particular aircraft design is to refer to its critical component analysis. Specifically, the kill tree (or kill expression) provides a clear presentation of these relationships, for a given kill level (i.e. degree of performance degradation), in a given flight phase (eg. take off, climb out, en route cruise, etc.). The task of developing the knowledge base for the Survivability Manager's vulnerability reduction logics can be further simplified by encoding the failure modes and effects analysis (FMEA) along with the fault tree analysis (FTA) conducted for that aircraft into the knowledge base. When thoroughly performed, this study reveals not only the result of a particular component failure but also any backup systems capable of performing its function. This information, along with

component functional status, comprises the necessary data required by the inference engine to correctly deduce and compensate for the failed component.

C. RELATED RESEARCH

1. Pilot's Associate (PA)

Underwritten by the Defense Advanced Research Projects Agency (DARPA) through its Strategic Computing Program (SCP), the Pilot's Associate is being developed by the Air Force's Wright Aeronautical Laboratory (AFWAL). Essentially, it is expected to assist the single seat fighter pilot by providing 'phantom flight crew' (i.e. copilot, weapon system operator, navigator, and flight engineer) expertise in both critical and non-critical situations. Initially, it will consist of four interactive expert systems [Ref. 11:pp 8-12]:

(1) A Situation Assessment Manager to assess the external environment as well as internal resources.

(2) A Tactical Planning Manager to recommend optimum tactical employment of the aircraft, given mission objectives and restrictions.

(3) A Mission Planning Manager to refine and redefine mission objectives, given current situation, command, and intelligence inputs.

(4) A System Status Manager to monitor and diagnose total system health and current/projected status of all on-board systems.

The Survivability Manager proposed in this thesis is partially assimilated to different degrees by each of the

PA's four defined managers. If it were included as a separate manager, it would interact with the other 'managers' to provide the pilot with an assistant whose primary purpose is to manage the lower level survivability decision processes.

2. Self-Repairing Flight Control System (S/R FCS)

This is another AFWAL research project. The S/R FCS will maintain post failure flight stability in fly by wire (FBW) flight controls by reconfiguring the multiple redundancies in control surfaces. Current FBW aircraft do not have this capability to recognize and account for structual damage through modification of the control laws that govern FBW operation [Ref. 12:pp 4-8]. Although originally developed for use in the Advanced Tactical Fighter (ATF), the principles would apply to all future combat aircraft and may even find limited applicability in retrofitting existing models. The SM could provide the S/R FCS with the functional status of the various flight control components, so that raconfiguration may be as smooth and effective as possible.

3. Fully Automatic Digital Engine Control (FADEC)

Under development at the Naval Weapons Center, a major goal of the FADEC program is to significantly reduce engine vulnerability by fully automating the regulation of engine controls. Given a thrust requirement from the pilot, the system would adjust the control configuration to provide

optimum (post-battle-damage) performance. Algorithms are being developed to make the appropriate adjustments, once the trouble has been identified [Ref. 13]. AI will undoubtedly provide the means to make the identification, based on available sensor data.

4. Computerized Automatic Test Equipment

Conducted by the Navy Research Laboratory, the investigation centers around the development of a computer generated testing strategy leading to implementation of software for Built-in-Test (BIT) equipment [Ref. 14:p. 67]. This would provide the SM with a fault detection/isolation capability enabling rapid evaluation and reconfiguration of functional subcomponents.

5. Collision Avoidance System (CAS)

On board collision avoidance systems are currently being independently developed by several avionics firms to give pilots advance warning in situations where collision with other aircraft is imminent. The CAS uses a miniaturized version of the ground based air traffic control radar which interrogates transponder equipped aircraft (most are) in the vicinity for barometric altitude. This information, along with accurate range and bearing information provided by the radar itself, is used to predict collision hazards [Ref. 15:pp 48-53]. There are various schemes used to advise the pilot of these hazards and to suggest avoidance maneuvers, but none use AI. Certainly, such a system could be

integrated with the SM to subtly initiate the avoidance maneuvers even before the pilot is aware of the hazard.

6. Terrain Avoidance Radar

These radars are sophisticated versions of the simple radar altimeter which is found on all IFR certified aircraft. In both cases, their function is to provide accurate ground clearance information. This information is analyzed by either the pilot or the automatic pilot, in terrain following or terminal approach evolutions. It could also be made available to the SM as a backup monitor to warn against, and possibly prevent, unintentional collision with the ground or water.

7. Wind Shear Detection and Alerting System

Built by Sperry Corporation as a part of the Performance Management System (PMS) and currently under company evaluation, this system senses significant changes in horizontal and vertical relative wind velocity (wind shear) and alerts the pilot with advisory lights, so that appropriate compensation can be initiated well before the pilot could otherwise detect the hazard [Ref. 16:pp. 30]. By feeding this information directly to the autopilot, the SM could initiate corrective action even sooner.

8. Integrated Electronic Warfare System (INWES)

The INWES program is expected to enhance aircraft survivability by providing crew members with electro-optical and elctromagnetic threat warning and, if required, indicate

an appropriate countermeasure response. Weapon system synergism is effected by using information provided by other on board sensors and subsystems, such as communications, navigation, and external sensors [Ref. 17:pp. 31-34]. INWES primary processing is an obvious candidate for KBS application.

VI. DESIGN REQUIREMENTS

Given the benefits of a Survivability Manager in the cockpit to assist the pilot in survivability management, the most challenging task to be undertaken (aside from funding) is the actual design and construction of the SM. The first step towards this goal is to define exactly what functions the SM is expected to perform. Once this is done, it remains to determine whether the required hardware, software, and sensors exist in practical form. If not, is the technology available to fabricate them? Finally, the system must be tailored to the specific systems and physical constraints of its parent aircraft.

A. FUNCTIONAL REQUIREMENTS

In order to define the functional requirements for the SM, it is useful to first characterize the pilot's duties and responsibilities with regard to survivability. The pilot might be considered a physician of sorts, and his aircraft a patient. He must constantly be aware of the health of his aircraft. He must rapidly and accurately diagnose any problems and prescribe a suitable remedy. Of course, a real doctor would have the benefit of easy access to exhaustive reference material, as well as the invaluable 'second opinion' from other doctors. With the advent of AI, the

physician has also been given the means to obtain this second opinion from a machine. MYCIN is an example of such a medical expert system, one that is concerned with blood infections and meningitis infections. Via interactive consultation, the doctor inputs the symptoms and vital statistics, and MYCIN produces a diagnosis and recommends appropriate therapy [Ref. 18:pp. 39-44]. Clearly, this Survivability Manager for people can find useful application to aircraft, with an appropriate knowledge base. The major difference is that the health would be directly monitored by the SM.

The Survivability Manager can be designed to perform a myriad of tasks which would otherwise require excessive pilot action or consideration. Regardless of the scope of involvement, the system must accomplish its tasking in five basic phases: monitor, predict, detect, analyze, and respond.

1. <u>Monitor Aircraft Health and External Environment</u>

The human brain can not reason without data, and the expert system is no different in this respect. They both require a nervous system, with suitable internal and external environment sensors, to gather and convey this data. In the cockpit, the data required can be obtained either by direct sensor relay, or indirectly by subsystem self-diagnostics polling.

External sensors provide the data required by the susceptibility reduction logics to forecast external hazards.

Examples include radar altimeter and collision avoidance radar. Internal sensors can be further subdivided into susceptibility reduction sensors and vulnerability reduction sensors. Susceptibility reduction sensors are concerned with control and actuator position reporting, providing positive feedback while monitoring normal and emergency procedures. If critical steps are omitted or transposed, susceptibility goes up for the hazards these procedures are established to avoid. Vulnerability reduction sensors report component and/or subsystem failure mode and degree. A complete, current picture of aircraft health is required for vulnerability reduction logics to determine the most effective subsystem reconfiguration possible.

2. Predict Hazards

The susceptibility reduction logics rely on external and internal sensors to provide thedata pertaining to proximity to hazardous conditions. To be effective, these logics must be able to deduce the hazard well before it precipitates any component failures. This requires a cause-and-effect reasoning capability which the expert system can theoretically supply. By extrapolation, the hazard may be argued to include equipment malfunction and pilot oversight. For example, a combat aircraft executing covert ingress to the target may unintentionally be radiating some form of electromagnetic energy. Note that, in this example, the logics must be cognizant of the flight mission and phase.

This would suggest an interface with the 'mission manager of the Pilot's Associate program, under development at the Air Force Wright Aeronautial Laboratory.

3. Detect and Isolate Failures

When a hazard can not be avoided, its damaging affects must be sensed before suitable vulnerability reduction measures can be applied. Failure mode and degree must be accurately reported to ensure the widest possible range of corrective actions available. Failure mode is the nature of functional degradation, while failure degree is the measure of its completeness. For example, a failure mode for an engine may be a partial loss of thrust with a degree of eighty-five percent maximum rated thrust available. The precise determination of the mode and degree of component failures requires a high degree of sensor sophistication and proliferation. Fortunately, most subsystems in modern aircraft are constructed with built-in-test circuits which can provide the bulk of this information. The remainder will have to be gathered by sensors designed for specific survivability applications. For example, sensors designed to report structural removal and over-stress conditions would prove invaluable in real time determination of performance limits.

4. Determine Optimal Response

In a multi-factored scenario, such as an aircraft in flight, there can be several plausible alternatives to act

upon at any given decision point. Only one can be selected, and a great deal of time can not be consumed in the selection. A knowledge based system with sufficient memory available can, in theory, identify and explore each viable alternative and present them to the pilot. Further, it can prioritize the list by optimal consistancy with flight safety and mission objectives. This is the essence of the utility of the expert system in survivability enhancement; the ability to determine the best course of action based on the analysis of internal and external data, given pre-defined non-numeric constraints.

5. Advise or Act

Once presented with the various alternatives, the pilot may or may not choose to act on the one that the expert system suggests. His decision would be based on factors it has not been provided for consideration. For example, the pilot may be the lead in a two plane flight, in which case the impact of his actions on his wingman must be considered. Conversely, it is conceivable that the situation may dictate an immediate response to prevent a catastrophic failure. A case in point is a sudden wind shear during final approach, resulting in excessive vertical drop. A properly programed expert system with suitable control interfaces could initiate compensation procedures well before the pilot could react, increasing the chances of surviving the hazard.

Clearly, an enable switch must be provided to give the pilot the prerogative to allow the expert system to act autonomously. Further, the pilot should be able to select the type and degree of autonomous tasking that the expert system is allowed to perform. In any case, the SM must inform the pilot of any actions taken.

B. SYSTEMS REQUIREMENTS

Today, the AI discipline is largely within the pure research stages, with a limited number of systems thus far developed for solving problems of modest complexity. However, enough is known to estimate general system requirements for an expert system for practical applications.

1. Hardware

The Survivability Manager must be able to react in real time to a dynamic, complex set of internal and external conditions. This equates to a need for extremely high speed processors and access to very large memories.

a. Processors

The so-called 'super computers', employing the conventional Von Neumann serial processing architecture, are being built with clock cycle times close to their minimum useful limit. Since an electrical pulse can only travel .3 meters in a nanosecond, the clock rate is beginning to constrain the very size of the computer. And yet, a nanosecond may not be small enough in a serial processor for

the enormous number of inferences per second required of an SM of modest capability. Goodyear Aerospace's Massively Parallel Processor (MPP) is an example of a new approach to this problem, one that may prove both faster and cheaper [Ref. 19:pp. 20-28]. The MPP design is essentially a physical representation of the 'parallelism' problem solving technique listed in Chapter VI. By building a system with hundreds, or even thousands, of processors which operate independently, the solution space search can theoretically be completed in a corresponding fraction of the time. However, there are some major obstacles to the development of parallel processing machines for practical AI applications. For example, processor interconnections and memory access schemes must provide for efficient use of available processing capabilities. Moreover, some means must be devised to break down the problem and equitably distribute the pieces.

b. Memory

It has been said that knowledge is power, and this is painfully evident to expert systems engineers. They have found that the size of the knowledge base is even more important than the efficiency of the inference engine. DARPA has estimated that a 10,000 rule expert system is the minimum size that could have practical military applications. Most currently operational expert systems have fewer than 500 rules. The implication is that massive memory facilities must be accessible to the SM, facilities that are not

currently available. The current expert system computer architecture utilizes an 18 bit address, providing a maximum of 262,144 addresses. The 32 bit address computer, providing for a maximum of 4.3 billion addressable memory locations, is seen as the logical choice for future expert systems.

2. Software

The expert system can not be efficiently programmed using a conventional language, such as FORTRAN or PASCAL. To fill this need, declarative languages have been developed specifically for KBS applications. Currently, the two most widely used expert system programming languages are "LISt Processing" (LISP) and "PROgramming in LOGic" (PROLOG). Both of these languages are effective building tools, but there are significant differences. LISP is useful because it manages data structures easily, and its programs can manipulate other programs, but it has no tools for logic programming. PROLOG is useful because it is essentially a compiler into which the user merely inputs the encoded knowledge base. The usual programming skills are not required. However, this ease of implementation is also a disadvantage, because it allows no efficient mechanism for closely controlling a procedural activity. The KBS language of the future will undoubtedly attempt to assimilate the best of both languages.

3. Knowledge Acquisition

This is the greatest single challenge to the realization of the SM. The SM must have access to properly encoded domain knowledge, and lots of it. Although there is no shortage of aircraft systems expertise, getting this knowledge into a form that is useful to an expert system is an extremely tedious, and not always successful, process. Researchers have found that often times a domain expert (eg. the pilot) may not be able to explain his/her reasoning in a particular situation, though he/she is unerring in his/her assessment.

4. Data Acquisition

Although domain knowledge is essential to the operation of the SM, it will be of no value to the pilot if it can not be applied to his current situation. The SM must also be able to sense the internal health and status of the aircraft systems, as well as the external environment. This can be accomplished through distributed resource sharing with the dedicated microprocessors in the various aircraft functional subsystems, or by direct sensor relay.

a. Resource Sharing

Most of the major systems in current commercial and military aircraft models have imbedded mircroprocessors that automate the operation of those systems for the pilot. The system status reports they receive from the components they control could theoretically be passed to the SM. The

physical interconnection scheme used to accomplish this transfer must account for the differences in architecture between the processors involved.

b. Dedicated Sensors

If resource sharing is not feasible or system status reports are otherwise not available for critical components, then sensors must be fitted to the components; sensors that report directly to the SM. Precise functional information may be required (i.e. failure cause, mode, and degree), which then requires a corresponding sophistication in sensor design.

C. COMPATIBILITY CONSIDERATIONS

Assuming that it is possible to build a competent Survivability Manager KBS, one of the last major design tasks is to build it within the physical constraints of the parent aircraft. This requirement is at odds with the systems requirements. To limit the acceptable volume and weight allocation necessarily limits the maximum processing and memory storage capabilities. Of course, this is a problem for avionics in general.

1. Integration with Projected Aircraft

In keeping with the philosophy that survivability should be designed in and not just added on, it is obvious that the Survivability Manager will be most successful when it can be incorporated into the earliest stages of the parent

aircraft's development. This is especially important for the SM, because it must be able to sense the functional health of the aircraft in depth.

2. <u>Retrofit with Existing Aircraft</u>

Existing aircraft may not be operational by the time a working SM of practical importance is finally available. Should major breakthroughs in research (funding) occur, it will be extremely costly to effectively integrate the SM with these aircraft. It may even be too late for next generation aircraft, such as the ATA and the ATF. This because the intimate interfacing that must be considered in the design now can not rely on AI practical success later on.

VII. SUMMARY AND CONCLUSIONS

A. SUMMARY

In spite of intensive safety engineering and well developed flight procedures, civil aircraft survivability is challenged by the hazards associated with the modern operational flight environment. For the military aircraft that is operating in a man-made hostile environment, these hazards are compounded by hazards which are specifically intended for the destruction of aircraft. Regardless of the type of mission to be flown, the primary responsibility of the pilot is the safe, effective employment of the aircraft, and his/her performance is seriously degraded by these hazards. U. S. National Transportation Safety Board statistics reveal a general decline in civil aircraft accidents in the last decade, but there are still too many, and a large portion of these accidents can be at least partially attributable to pilot error. Statistics for military flight mishaps show a similar pattern. Pilot error is often the result of task overload conditions. This conclusion is based on the fact that most accidents occur during critical flight phases when the pilot task load is greatest.

Conventional task load reduction practices seek to enhance aircraft survivability by automating the execution of

pilot-selected aircraft system functions. Although this automation allows the pilot to manage several of the aircraft systems simultaneously, it can lead to a 'data rich - information poor' cockpit if the number or complexity of the systems involved is great. This data rich condition will in fact decrease the aircraft's survivability if the pilot commits a procedural error while sorting through nonprioritized and/or extraneous data. It is clear that relegation of task management, as well as simplification of task execution, is required to effectively reduce pilot workload during critical flight phases. If larger crews or improved pilot capabilities are not feasible approaches for enhanced task management , then the avionics engineer must build 'intelligent' sytems that can manage themselves. These automated Survivability Managers (SM) would monitor aircraft health and the external environment, and react to recognized hazards in ways that complement or even supplement pilot capabilities.

Knowledge based systems (KBS), which are considered studies within the field of artificial intelligence (AI), are ideally suited to provide the pilot with an automated Survivability Manager. The KBS relys on sophisticated problem solving techniques and vast stores of domain-specific knowledge to solve problems that conventional language programs can not solve. The conventional programming languages (e.g. FORTRAN) rely on numeric methods to solve

problems and can not efficiently handle problems involving non-numeric relationships. In contrast, the declarative languages used in knowledge based systems can employ human-like reasoning techniques and strategies. Conceptually, the KBS consists of a knowledge base and an inference engine. The knowledge base contains the domain-specific knowledge (provided by domain experts) required to solve domain-specific problems. The inference engine performs the actual reasoning process by employing some suitable combination of reasoning techniques and strategies. The application of KBS principles to survivability management is illustrated in Chapter IV, using a hypothetical engine fuel supply system as a working example.

Once the KBS capabilities are understood, the applications to survivability enhancement are readily apparent. In a military aircraft, the Survivability Manager could detect, analyze, classify, and respond to threat emitters and propagators through the integrated management of the available susceptibility reduction features and equipment. In a civil aircraft, susceptibility reduction would be accomplished by pooling the external and internal sensor resources to prevent damage due to environmental extremes, material overstresses, and human errors. The SM can assist with vulnerability reduction in both civil and military aircraft through control of active damage suppression and/or component redundancy features. The

development of the SM can draw upon the efforts of the Pilot's Associate, the Self-Repairing Flight Control System, the Fully Automatic Digital Engine Conrol system, and several other related research projects.

The SM can be designed to manage a number of distinct aircraft survivability enhancement operations, but in all cases this management must be performed in five basic phases:

(1) Monitor aircraft health, and the external environment.
(2) Predict hazards.
(3) Detect and isolate failures.
(4) Determine the optimal response.
(5) Advise the pilot, or act autonomously.

Aside from these functional requirements, there are systems requirements that must be considered by the SM designer. Processing speed must be fast enough to allow the SM to react immediately to real or perceived hazards. Memory storage space must be sufficient to include the enormous amount of knowledge needed. The programming language should allow for ease of knowledge infusion, yet be flexible enough to apply a number of reasoning techniques and strategies. Systems status data must be made accessible via resource sharing and dedicated sensors. Finally, the system must fit gracefully into the parent aircraft, preferably during the early aircraft design stages.

B. CONCLUSIONS

1. Feasibility

The knowledge based system is an emerging technology. The KBS has already been proven in small scale applications, and has even begun to enjoy significant commercial development. Although a system which is large enough to accomodate a Survivability Manager with modest capabilities (on the order of 10,000 rules) has yet to be built, the potential certainly exists. Of course, the first such system may not fit into a C-5's cargo bay, let alone an F/A-18's avionics suite. But even the single seat fighter pilot will one day realize the benefits of an intelligent cockpit. The capability for relegating lower level management processes is sorely needed now, especially during the task-load-saturated critical flight phases. Through AI, the Survivability Manager will meet this challenge, but only after intensive research and development efforts.

2. Recommendations for Further Research

There are a number of studies which must be conducted to further investigate the feasability of building a Survivability Manager. Although these studies will rely on basic AI research, they should be centered on the specific needs of the intelligent cockpit. The first study might consist of defining a modest 200 rule KBS for an isolated system in an actual aircraft, such as the F/A-18 power plant. The aircraft's critical component analysis along with the

flight systems manual will provide an excellent source of basic knowledge for this purpose. Next, the method of representing the knowledge in the knowledg base must be considered. This entails selection of the hardware and software to host the expert system. This selection will be limited by available assets. Once the knowledge has been properly encoded, a harness must be constructed to simulate the various aircraft health status inputs required by the SM prototype. Finally, the system should be tested using realistic performance and failure data from the actual aircraft. The SM prototype can then be tested under various simulated adverse conditions to assess and refine the correctness and timeliness of its responses. These studies will not be conclusive, but they should be indicative of the promise of AI for enhanced aircraft survivability.

APPENDIX A (GLOSSARY)

ACTIVE DAMAGE SUPPRESSION- An aircraft vulnerability reduction technique, wherein damage is sensed and subsequently minimized or contained through activation of one or more devices.

AIRCRAFT COMBAT SURVIVABILITY- The ability of an aircraft to avoid or withstand (damage caused by) a man-made hostile environment.

AIRCRAFT COMBAT SUSCEPTIBILITY- The inability of an aircraft to avoid (damage caused by) a man-made hostile environment.

AIRCRAFT COMBAT VULNERABILITY- The inability of an aircraft to withstand (damage caused by) a man-made hostile environment.

AIRCRAFT HEALTH- The functional condition of the aircraft, measured by its operational performance capabilities, and dependent on the functional condition of its systems and system components.

AIRCRAFT SURVIVABILITY- The ability of an aircraft to avoid or withstand (flight performance degradation caused by) a hazardous situation.

AIRCRAFT SUSCEPTIBILITY- The inability of an aircraft to avoid (flight performance degradation caused by) a hazardous situation.

AIRCRAFT VULNERABILITY- The inability of an aircraft to withstand (flight performance degradation caused by) a hazardous situation.

ARTIFICIAL INTELLIGENCE- The condition where machines mimic human rational thought processes.

BACKWARD INFERENCING- A reasoning strategy wherein a solution to a problem is assumed and a search for supporting evidence is then pursued sequentially backwards to the known facts.

COMPONENT REDUNDANCY- A vulnerability reduction technique wherein a function can be performed by more than one component or groups of components.

CRITICAL COMPONENT- A component which makes a necessary contribution to the performance of a flight essential function. The loss of a redundant critical component will not neccessarily result in a loss of a flight essential

function, whereas the loss of a non-redundant critical component will always result in the loss of a flight essential function.

CRITICAL FLIGHT PHASE- A portion of the flight in which the aircraft is especially susceptible to hazardous situations.

DOMAIN EXPERT- A person that is recognized as an authority in the specific subject of interest and from whom knowledge is acquired for a knowledge based system.

DOMAIN KNOWLEDGE- The knowledge that an expert in the subject of interest provides to the KBS.

EXPERT SYSTEM- See KNOWLEDGE BASED SYSTEM

FAILURE CAUSE- A primary event which significantly contributed to the failure mode of a component.

FAILURE DEGREE- The extent or completeness to which a component's performance has been functionally degraded.

FAILURE MODE- The nature of a component failure. For example, a control rod may be either severed or jammed.

FAILURE MODES AND EFFECTS ANALYSIS (FMEA)- A procedure that (1) identifies and documents all possible failure modes of a component or subsystem, and (2) determines the effect of each failure mode upon the capability of the system or subsystem to perform its essential functions.

FLIGHT ESSENTIAL FUNCTION- A system or subsystem function required to enable the aircraft to sustain controlled flight.

FORWARD INFERENCING- A reasoning strategy wherein a search for a problem solution is conducted sequentially from the known facts.

INFERENCE ENGINE- The construct within the KBS that performs the reasoning process.

INSTRUMENT FLIGHT RULES (IFR)- FAA supervised flight procedures wherein the aircraft route, altitude, and airspeed is dictated by ground controllers.

KNOWLEDGE BASED SYSTEM (KBS)- A computer system that uses sophisticated non-numeric problem solving techniques and vast stores of knowledge to solve problems beyond the reach of conventionally programmed computers.

KNOWLEDGE BASE- The construct within the KBS that contains the encoded domain knowledge.

MAN-MADE HOSTILE ENVIRONMENT- Flight conditions that are hazardous to flight safety due to the intentional employment of destructive man-made devices.

SURVIVABILITY MANAGER- A knowledge based system designed to assist the pilot in the management of the aircraft's survivability features and equipment.

VISUAL FLIGHT RULES (VFR)- Flight procedures wherein the pilot is solely responsible for the safe conduct of the flight and is not under direct ground supervision.

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